

# First phase diagram of hadronic matter

Consider phase transition of hadronic matter at nonzero:

$T$  = temperature and  $\mu$  = quark chemical potential ( $= 1/3$  baryon chem. pot.)

Cabibbo and Parisi '75: Exponential (Hagedorn) spectrum limiting temperature,  
*or* transition to new, “unconfined” phase.

*Assume* “semi-circle” in plane of  $T$  and  $\mu$ . Today: there is *no* semi-circle

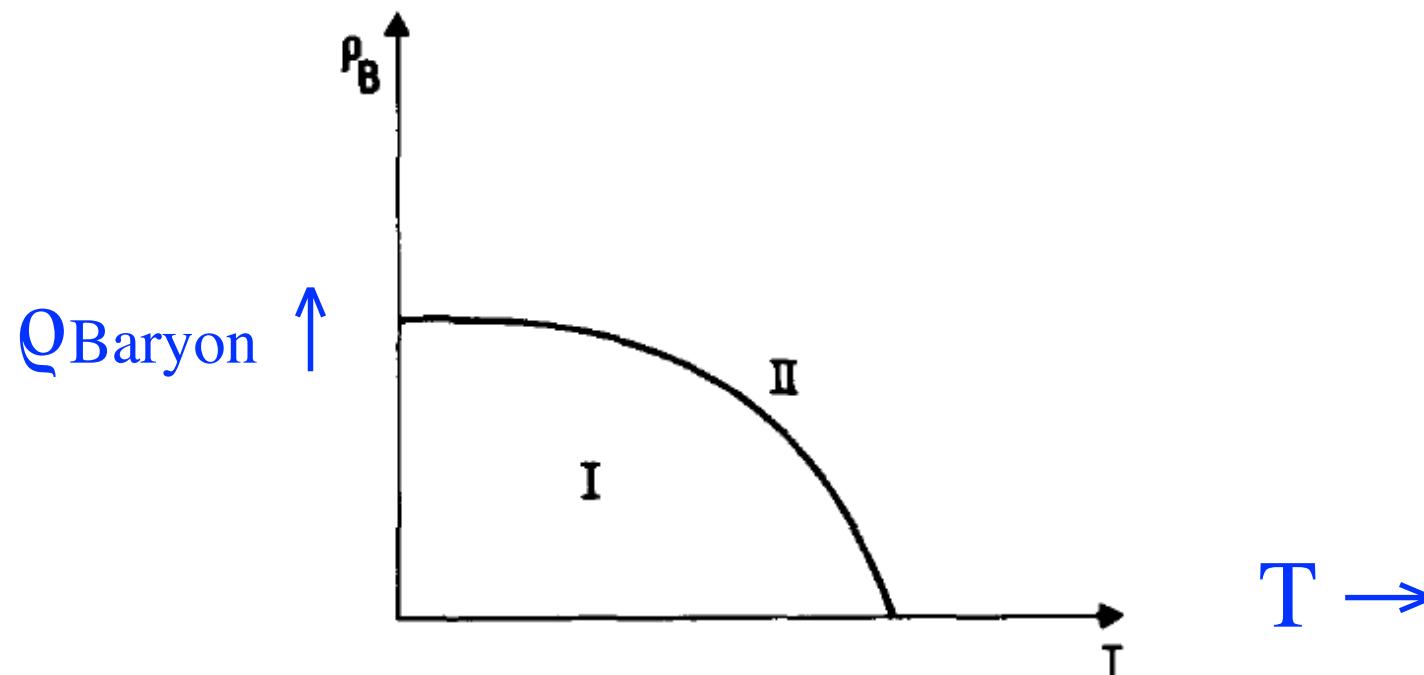


Fig. 1. Schematic phase diagram of hadronic matter.  $\rho_B$  is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

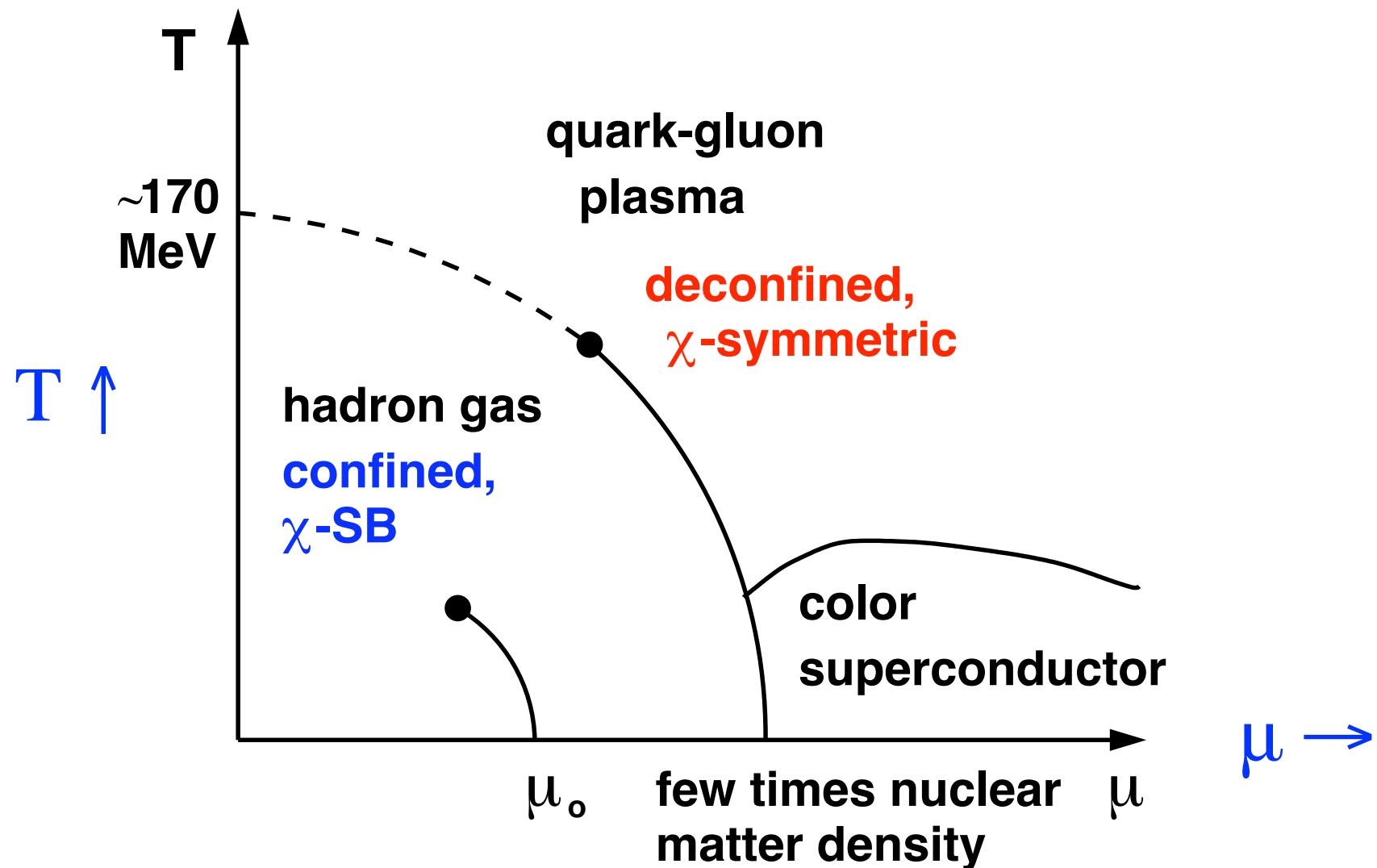
# Phase diagram, ~ '06

Lattice,  $T \neq 0, \mu = 0$ : two possible transitions; one crossover, same  $T$ . Karsch '06

Remains crossover for  $\mu \neq 0$ ? Stephanov, Rajagopal, & Shuryak '98:

Critical end point where crossover turns into first order transition

But still semi-circle in  $T$  and  $\mu$



# What is Quarkyonic?

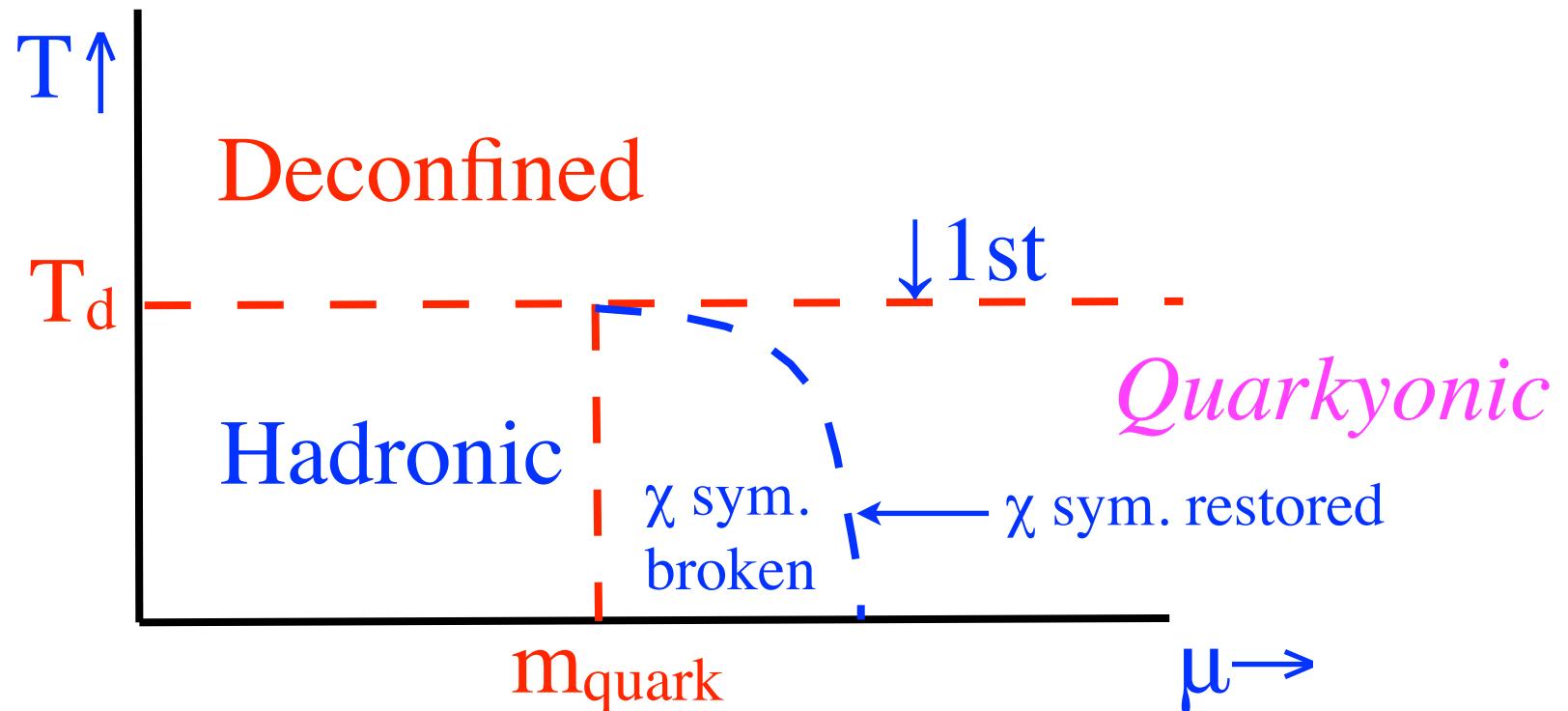
Debye mass at leading order:

$$m_{Debye}^2 = g^2((N_c + N_f/2)T^2/3 + N_f \mu^2/(2\pi^2))$$

Large number of colors, let  $N_c \rightarrow \infty$ , with  $g^2 \sim 1/N_c$  and  $N_f \sim 1$

$$T \neq 0 : m_{Debye}^2 \sim T^2 ; T = 0 , \mu \neq 0 : m_{Debye}^2 \sim 1/N_c \mu^2$$

$T = 0, \mu \neq 0$ : *confined* until *very large*  $\mu^2 \sim N_c$ . Consider  $\Lambda_{QCD} \ll \mu \ll N_c^{1/2}$ : pressure  $\approx$  perturbative, but excitations near Fermi surface confined: *Quarkyonic*



# Two colors on lattice: where is Quarkyonic?

Braguta, Ilgenfritz, Kotov, Molochkov, & Nikolaev, 1605.04090 (earlier: Hands, Skellerud + ...)

Lattice:  $N_c = 2$  (no sign problem!),  $N_f = 2$  staggered quarks

$m_\pi \sim 400$  MeV, fixed  $T \sim 50$  MeV, vary  $\mu$ . Find four “phases”:

$0 \leq \mu < m_\pi/2 \sim 200$  MeV. Hadronic phase: confined, no condensates

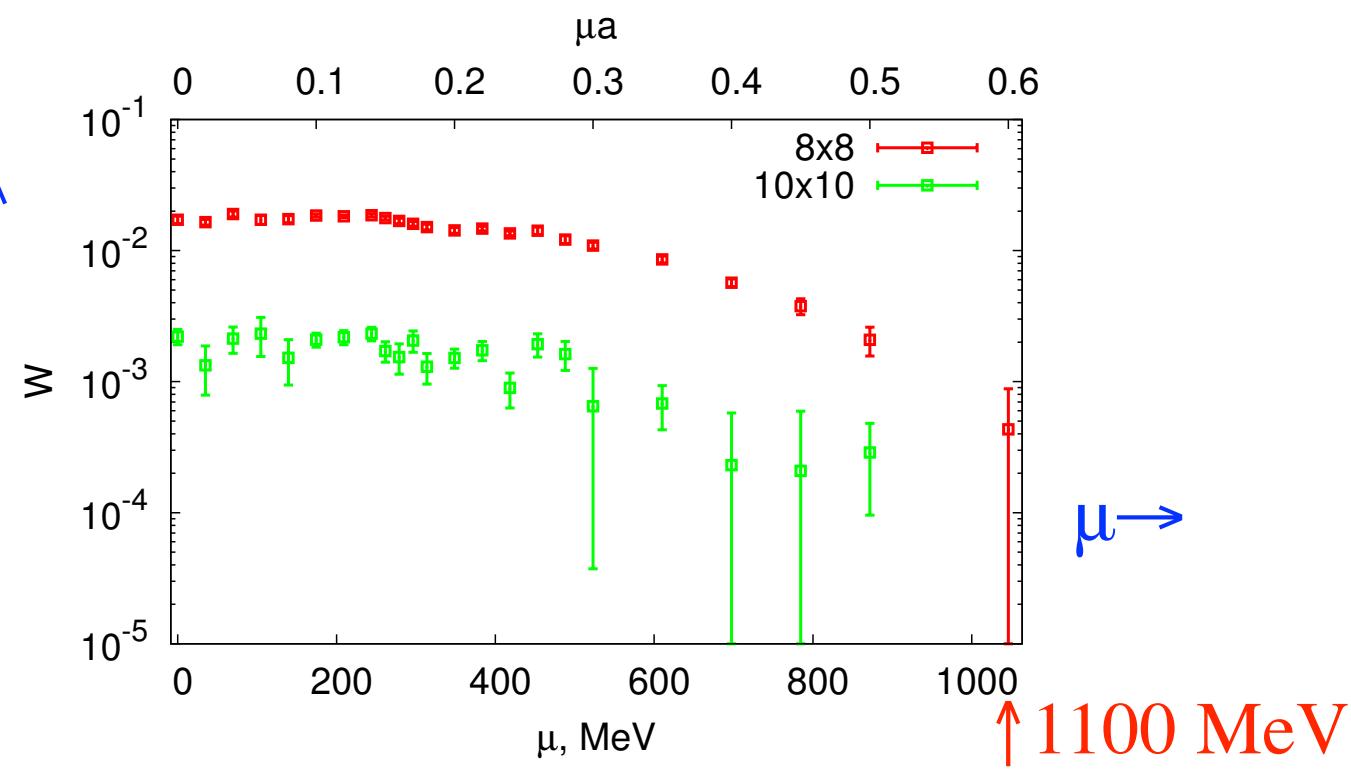
$200 < \mu < 350$ : Bose-Einstein condensate (BEC) of diquarks, “dilute baryons”

$350 < \mu < 600$ : BEC ( $\sim$ BCS), dense baryons (pressure  $\neq$  pert)

$600 < \mu < 1100$ : *Quarkyonic*: pressure  $\approx$  pert., but *confined* (Wilson loop area law)

Quarkyonic up to *highest*  $\mu > 1$  GeV.  $N_c = 2$  is *not* large  $N_c$

$\langle \text{Wilson loop} \rangle \uparrow$



## When is perturbation theory valid? $T \neq 0, \mu = 0$

Consider first  $T \neq 0$ : gluon propagator  $\Delta(p_0, p) \sim 1/(p_0^2 + p^2)$ ,  $p_0 = 2\pi n T$

Braaten & Nieto, hep-ph/9501375: dominant  $p \sim 2\pi T$

Laine & Schroder, hep-ph/0503061: by 2-loop calc. in effective theory, find for  $N_c = 3$ :

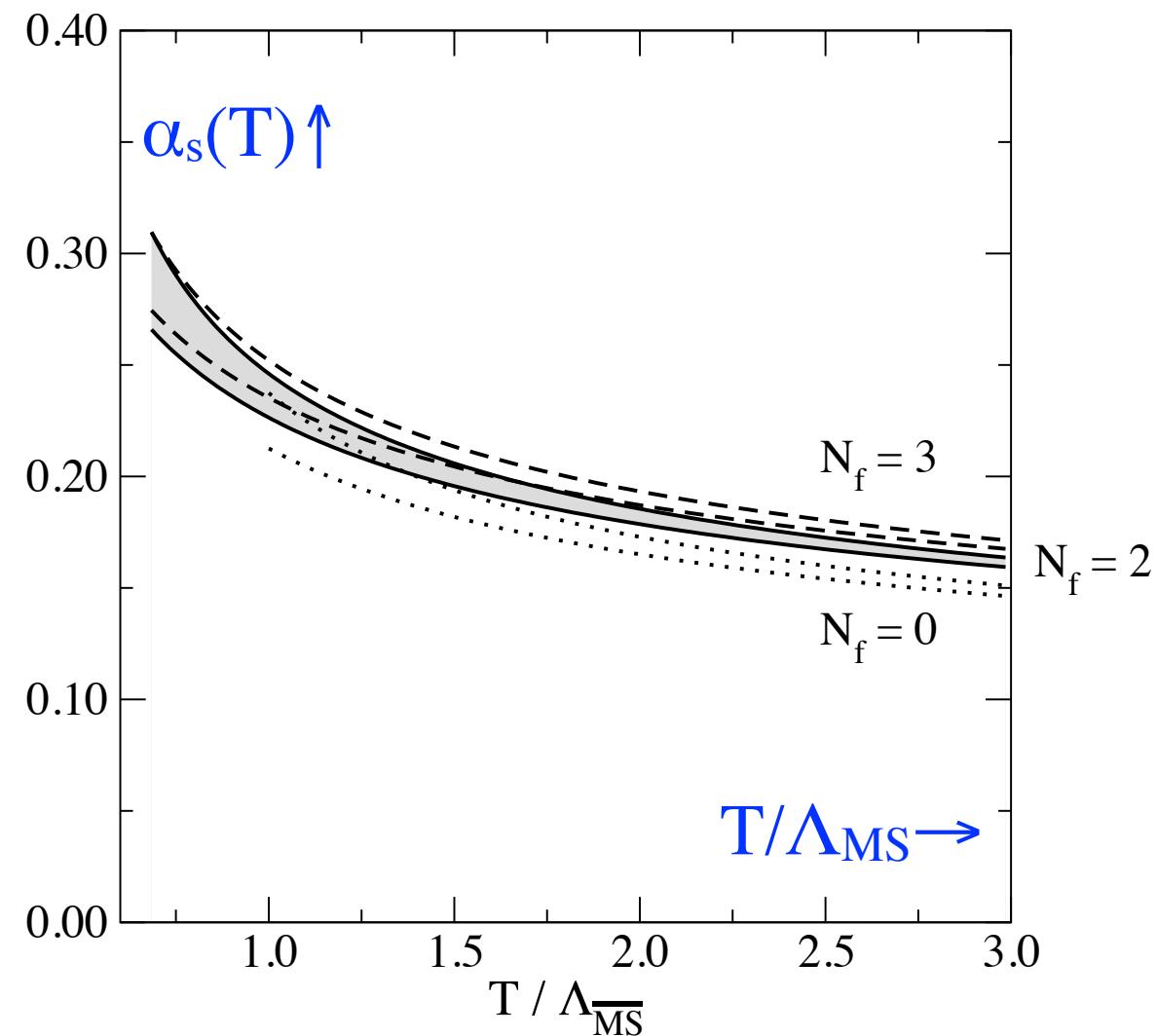
$$N_f = 0 : \Lambda_{pert} \sim 7T$$

$$N_f = 3 : \Lambda_{pert} \sim 9T$$

Band: change in effective  $\alpha_s(T)$ ,  
by varying  $\Lambda_{pert}$  by a factor of two.

Even down to  $T \sim 150$  MeV,  
 $\Lambda_{pert}$  is still  $\sim 1$  GeV.

N.B.: effective theory resums  
modes with  $p \sim T$ , then  $p \sim g T$ ,  
then  $p \sim g^2 T$ .

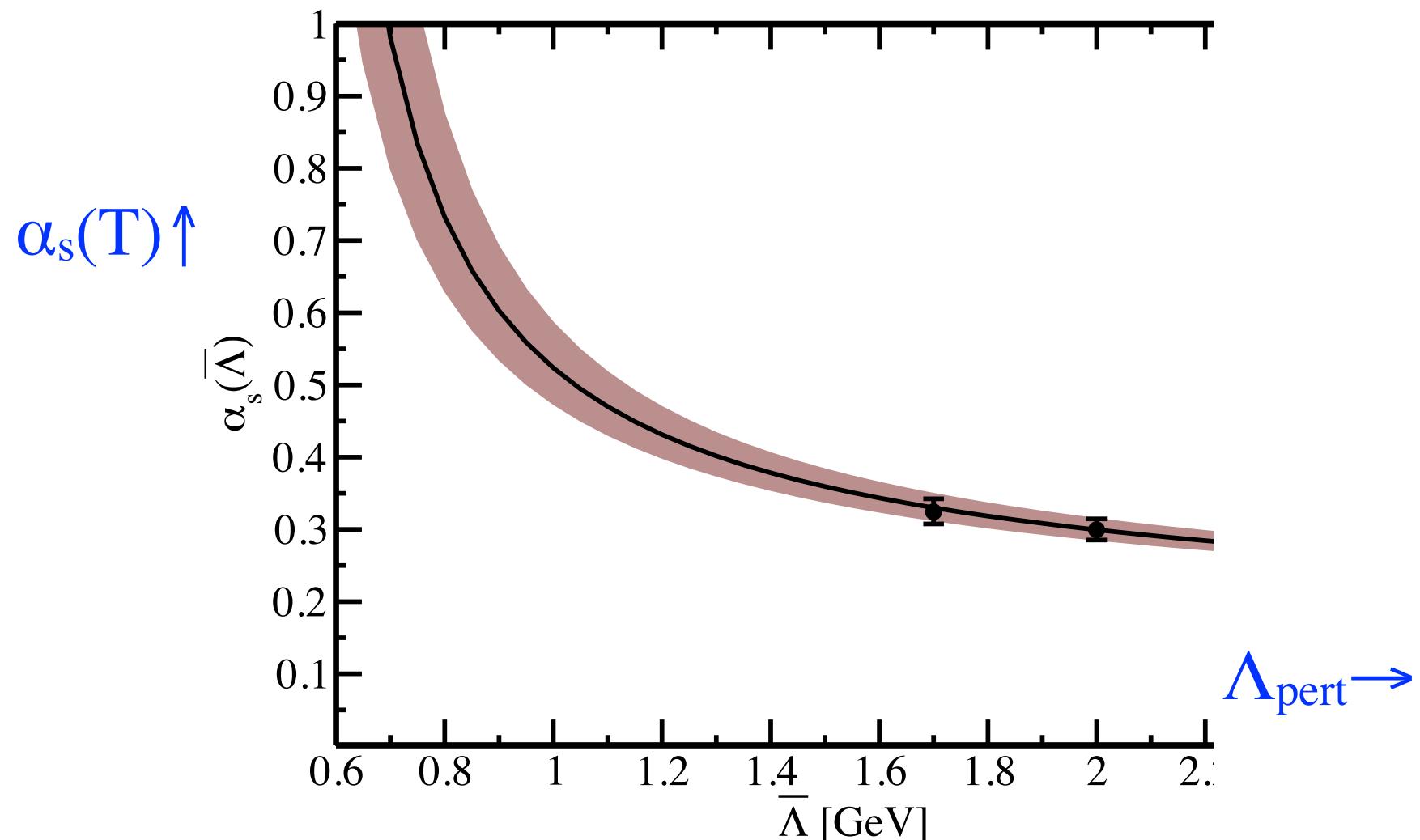


# When is perturbation theory valid? $\mu \neq 0$ , $T = 0$

Kurkela, Romatschke, & Vuorinen, 0912.1856: pressure to  $\sim \alpha_s^2(T)$ , 2+1 flavors ( $m_s \neq 0$ )

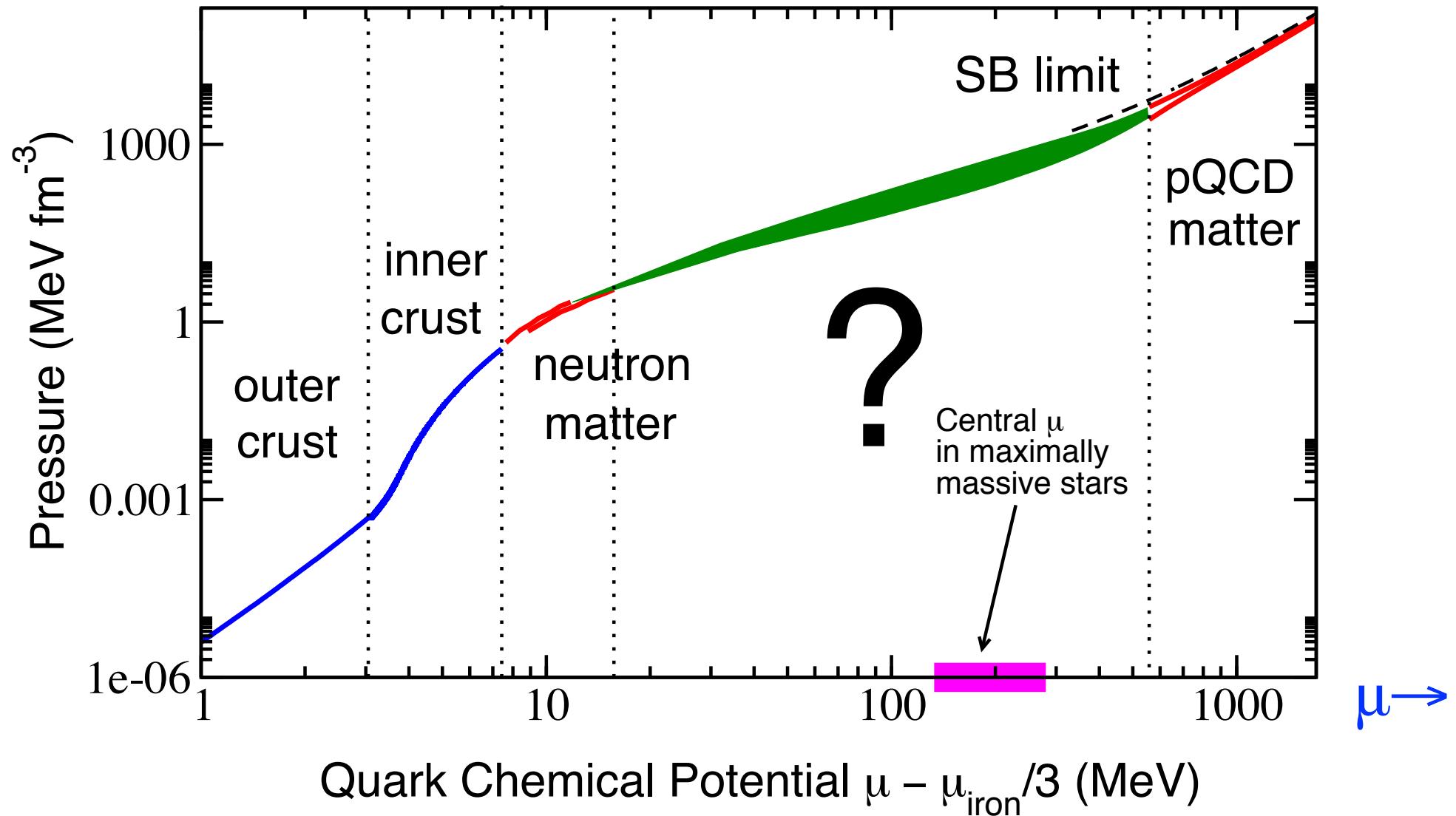
Take  $\Lambda_{\text{pert}}$  from Debye mass,

$$\Lambda_{\text{pert}} \sim m_{\text{Debye}}^2/g^2 = \sqrt{(2\pi T)^2 + (2\mu)^2} = 2\mu, T = 0$$



# When is perturbation theory valid? $\mu \neq 0$ , $T = 0$

Fraga, Kurkela, & Schaffner-Bielich, 1402.6618: using  $\Lambda_{\text{pert}} \sim 2 \mu$ :



# When is cold quark matter Quarkyonic?

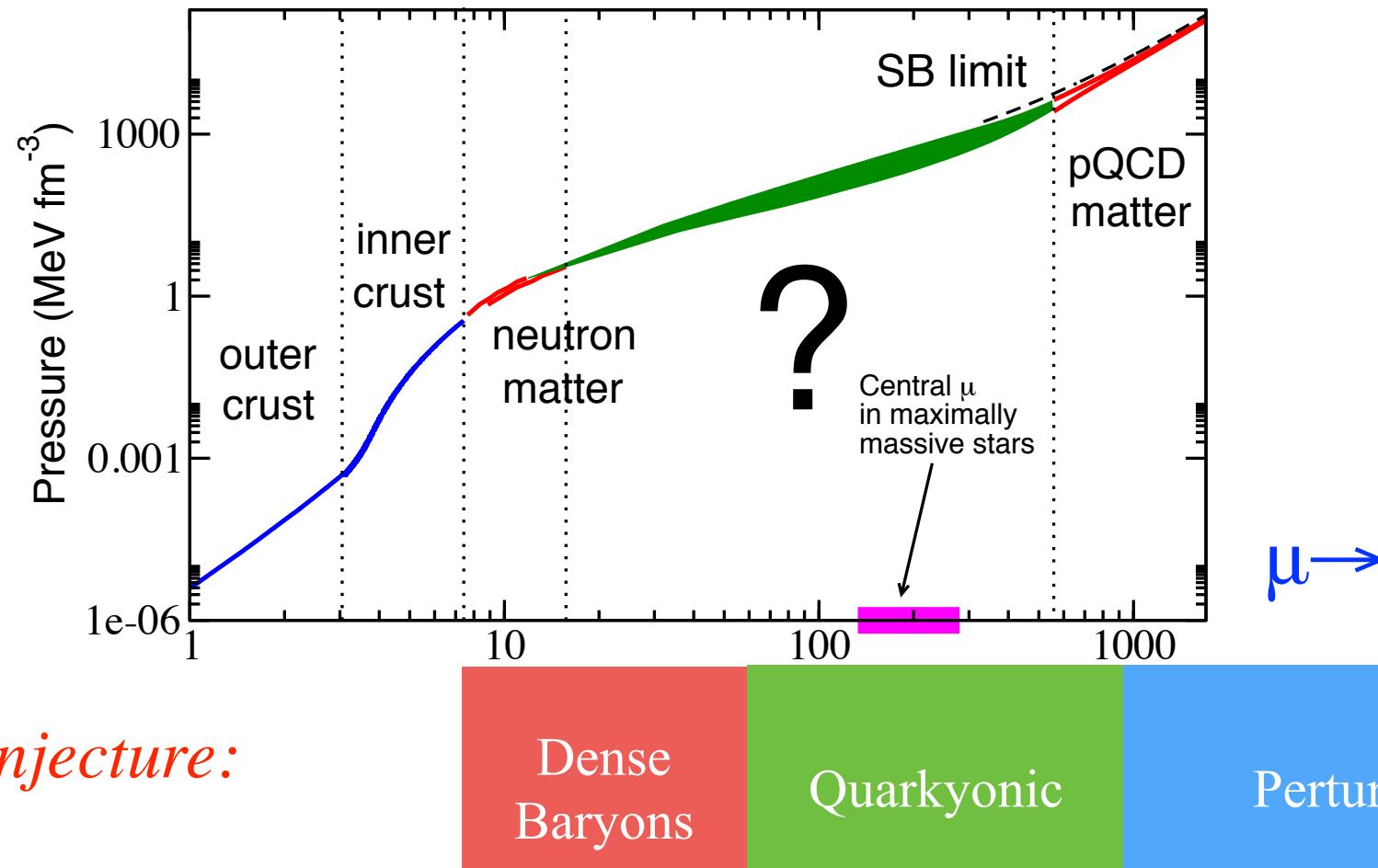
For perturbation theory in vacuum: valid for momenta  $p > \Lambda_{vac} = 1 \text{ GeV}$

Suggest: Fermi momenta is a momentum. In *strict* analogy to vacuum:

If  $\mu > 1 \text{ GeV}$ ,  $\Lambda_{\text{pert}} \sim \mu$ . For  $\mu < 1 \text{ GeV}$ , Quarkyonic or dense baryons.

Ghisoiu, Gorda, Kurkela, Romatschke, Säppi, & Vuorinen, 1609.04339: pressure( $\mu$ )  $\sim g^6$ .

Will be able to compute  $\Lambda_{\text{pert}} = \# \mu$ .  $\# \sim 1$ ?



Pure conjecture: